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TITLE: BODY STATE ESTIMATION OF A
                    VEHICLE

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BODY STATE ESTIMATION OF A VEHICLE

BACKGROUND

[0001] This invention relates to a system and method of estimating body states of a vehicle.

[0002] Dynamic control systems have been recently introduced in automotive vehicles for measuring the body states of the vehicle and controlling the dynamics of the vehicle based on the measured body states. For example, certain dynamic stability control systems know broadly as control systems compare the desired direction of the vehicle based on the steering wheel angle, the direction of travel and other inputs, and control the yaw of the vehicle by controlling the braking effort at the various wheels of the vehicle. By regulating the amount of braking torque applied to each wheel, the desired direction of travel may be maintained. Commercial examples of such systems are known as dynamic stability program (DSP) or electronic stability program (ESP) systems.

[0003] Other systems measure vehicle characteristics to prevent vehicle rollover and for tilt control (or body roll). Tilt control maintains the vehicle body on a plane or nearly on a plane parallel to the road surface, and rollover control maintains the vehicle wheels on the road surface. Certain systems use a combination of yaw control and tilt control to maintain the vehicle body horizontal while turning. Commercial examples of these systems are known as active rollover prevention (ARP) and rollover stability control (RSC) systems.

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[0004] Typically, such control systems referred here collectively as dynamic stability control systems use dedicated sensors that measure the yaw or roll of the vehicle. However, yaw rate and roll rate sensors are costly. Therefore, it would be desirable to use a general sensor to measure any body state of the vehicles, that is, a sensor that is not necessarily dedicated to measuring the roll or yaw of the vehicle.

BRIEF SUMMARY OF THE INVENTION

[0005] In general, the present invention features a system and method for estimating body states of a vehicle. The system includes at least two sensors mounted to the vehicle. The sensors generate measured signals corresponding to the dynamic state of the vehicle. A signal adjuster or signal conditioner transforms the measured vehicle states from a sensor coordinate system to a body coordinate system associated with the vehicle. A filter receives the transformed measured vehicle states from the signal adjuster and processes the measured signals into state estimates of the vehicle, such as, for example, the lateral velocity, yaw rate, roll angle, and roll rate of the vehicle.

[0006] The filter may include a model of the vehicle dynamics and a model of the sensors such that the states estimates are based on the transformed measured signals and the models of the vehicle dynamics and sensors. The filter may also include an estimator implemented with an algorithm that processes the transformed measured vehicle states and the models of the vehicle dynamics and sensors and generates the state estimates.

[0007] The present invention enables measuring the body states of a vehicle with various types of sensors that may not be as costly as dedicated roll or yaw rate

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sensors. For example, the sensors may all be linear accelerometers. However, in some implementations, it may be desirable to use an angular rate sensor in combination with linear accelerometers.

[0008]   Other features and advantages will be apparent from the following drawings, detailed description and claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009]   Figure 1 depicts a block diagram of the processing of the vehicle states in accordance with the invention.

[0010]   Figure 2 depicts a general array of sensors for measuring body states of a vehicle.

DETAILED DESCRIPTION

[0011]   In accordance with an embodiment of the invention, Figure 1 illustrates a system 10 that measures the vehicle states of a vehicle identified as block 12. Specifically, the system 10 includes a plurality of sensors 14 that measure signals which contain parts related to components of the vehicle states of the vehicle dynamics 16 produced, for example, when the angle of the steering wheel δ is changed.

[0012]   The system 10 also includes a signal conditioner or adjuster 18 that receives measured signals from the sensors 14 and a filter 20 that receives the adjusted signals from the signal adjuster 18. In certain embodiments, the filter 20 is a Kalman filter including a model of the vehicle dynamics 22 and a model of the sensors 24. These models are described below in greater detail.

[0013]   The signal adjuster 18 and the sensor model 24, which incorporates the model of the vehicle dynamics 22, provide inputs to an estimator 26. An

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algorithm with a feed back loop 28 is implemented in the estimator 26 to process the transformed signals with the models of the vehicle dynamics and the sensors. The output from the estimator 26 is the state estimates $\bar{x}_v$. The body states estimates may include the roll angle, roll rate, yaw rate, and lateral velocity, as well as other body states.

[0014] In some embodiments, the sensors 14 measure the linear acceleration at a particular location where the sensor is mounted to the vehicle. When the sensors are not aligned in a plane perpendicular to the axis of interest, the measured values contain biases proportional to the angular rates about other axes. Similarly, when the measurement axes of the sensing devices are not coincident, the measured values contain biases proportional to the angular acceleration about other axes. Moreover, when the measurement axes of the sensing devices are not coincident and are not mounted along a body reference axis, the measured values contain unique gravity biases dependent upon the difference in mounting angle of the sensors and the body lean angle of the vehicle.

[0015] To address these biases, a general implementation of the system 10 can be employed as illustrated in Figure 2. Here the sensors 14 (identified individually as S_1 and S_2) are in known and fixed positions on the vehicle body 12 and the orientation of the measurement axes of the sensors S_1 and S_2 are known and fixed. Specifically, the location and orientation of a sensor S_i is provided by the relation

$$P_i(x_i, y_i, z_i, \theta_i, \chi_i, \phi_i),$$ (1)

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where x_i, y_i, z_i are the space coordinates of the sensor S_i, θ_i is the sensor yaw angle, that is, the orientation of the sensor's measurement axis in the X_B, Y_B plane with respect to the X_B axis, χ_i is the sensor pitch angle, that is, the orientation of the sensor's measurement axis with respect to the X_B, Y_B plane, and ϕ_i is the sensor roll angle, which is the rotation about the respective measurement axis.

[0016] The sensors S_i measure the linear acceleration at the location Pi, namely, $\bar{a}_i = \bar{m}_i \cdot |m_i| = [a_{xi}, a_{yi}, a_{zi}]^T$, where $\bar{m}_i$ is the unit vector along the measurement axis, and $|m_i|$ is the magnitude of the acceleration along the measurement axis.

[0017] Since the acceleration $\bar{a}_i$ measured by the sensor S_i is the acceleration in the sensor coordinate system, the measured accelerations are transferred to a body coordinate system. In certain embodiments, it is assumed that in an array of single axis accelerometers each accelerometer has a measurement axis referred to as the x_{sensor} axis. Accordingly, the transformation from the sensor coordinate system to the body coordinate system is provided by the expression

$$\bar{a}_i \times \overline{Body}_i = \bar{a}_i \begin{bmatrix} x_{body,i} \\ y_{body,i} \\ z_{body,i} \end{bmatrix} = \begin{bmatrix} a_{x,body} \\ a_{y,body} \\ a_{z,body} \end{bmatrix} \qquad (2)$$

where

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$$\overline{Body}_i = \begin{bmatrix} x_{body,i} \\ y_{body,i} \\ z_{body,i} \end{bmatrix} = \begin{bmatrix} \theta_i c \chi_i c & -\theta_i s \phi_i c - \theta_i c \chi_i s \phi_i s & \theta_i s \phi_i s + \theta_i c \chi_i s \phi_i c \\ \theta_i s \chi_i c & \theta_i c \phi_i c + \theta_i s \chi_i s \phi_i s & -\theta_i c \phi_i s - \theta_i s \chi_i s \phi_i c \\ \chi_i s & \chi_i c \phi_i s & \chi_i c \phi_i c \end{bmatrix} \cdot \begin{bmatrix} x_{sensor} \\ y_{sensor} \\ z_{sensor} \end{bmatrix}$$

where

$_c = \cos(\_)$

$_s = \sin(\_)$

$\theta_i = sensor\_yaw\_angle$

$\chi_i = sensor\_pitch\_angle$

$\phi_i = sensor\_roll\_angle$

and $\begin{bmatrix} x_{sensor} & y_{sensor} & z_{sensor} \end{bmatrix}^T = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^T$, since x_{sensor} is assumed to be the measurement axis for each of the single axis accelerometers.

[0018]   Note that the transformation identified in Equation (2) is typically performed in the signal adjuster 18 (Figure 1). The signal adjuster 18 may also provide a DC bias offset compensation to compensate for the biases discussed above.

[0019]   Regarding the Kalman Filter 20, the model of the vehicle dynamics 22 for a state vector

$$\bar{x}_v = \begin{bmatrix} \dot{y}_v & r_v & \theta_v & \dot{\theta}_v \end{bmatrix}^T \tag{3}$$

is provided by the expression

$$\dot{\bar{x}}_v = A \cdot \bar{x}_v + B \cdot \bar{u} \tag{4}$$

where

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\begin{bmatrix} \ddot{y}_v \\ \dot{r}_v \\ \dot{\theta}_v \\ \ddot{\theta}_v \end{bmatrix} = \begin{bmatrix} -\dfrac{C_F + C_R}{mu} & \dfrac{C_R b - C_F a}{mu} - u & 0 & 0 \\ \dfrac{C_R b - C_F a}{I_z u} & \dfrac{-C_F a^2 + C_R b^2}{I_z u} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -\dfrac{h}{I_x u} & \dfrac{h(C_R b - C_F a - mu^2)}{I_x} & -\dfrac{K}{I_x} & -\dfrac{C}{I_x} \end{bmatrix} \begin{bmatrix} \dot{y}_v \\ r_v \\ \theta_v \\ \dot{\theta}_v \end{bmatrix} + \begin{bmatrix} \dfrac{C_F}{m} & 0 \\ \dfrac{C_F a}{I_z} & 0 \\ 0 & 0 \\ \dfrac{C_F}{m} & 0 \end{bmatrix} \begin{bmatrix} \delta \\ g \end{bmatrix} \quad (5)
$$

and where $\dot{y}_v$ = lateral velocity of the vehicle

r = yaw rate of the vehicle

θ_v = roll angle of the vehicle

$\dot{\theta}_v$ = roll rate of the vehicle

C_F = cornering stiffness of the front axle

C_R = cornering stiffness of the rear axle

a = distance from center of gravity to the front axle

b = distance from center of gravity to the rear axle

m = mass of the vehicle

h = height of the center of gravity above the roll axis

I_z = yaw moment of inertia

I_x = roll moment of inertia

C = vehicle roll dampening

K = vehicle roll stiffness

u = longitudinal vehicle speed

δ = steering angle of the tires

g = gravitational acceleration

$$\dot{*} = \frac{d}{dt} *$$

and $\ddot{*} = \dfrac{d^2}{dt^2} *$

[0020]   As for the model of the sensors 24, the model of laterally oriented sensors is provided by the expression

$$A_{y,meas} = \ddot{y}_v + \dot{r}_v d_{xtoYA} + \ddot{\theta}_v d_{ztoRA} + r_v u \tag{6}$$

Accordingly, since $A_{y,meas} = a_{y,body}$ from Equation (2), substituting the expressions for $\ddot{y}_v$, $\dot{r}_v$, $\ddot{\theta}_v$, and r_v from Equation (5) into Equation (6) yields the expression

$$a_{y,body} = \left[a_{11}\dot{y}_v + a_{12}r_v + \frac{C_F}{m}\delta \right] + \left[a_{21}\dot{y}_v + a_{22}r_v + \frac{C_F a}{I_z}\delta \right] d_{xtoYA}$$

$$+ \left[a_{41}\dot{y}_v + a_{12}r_v + a_{43}\,\dot{\theta}_v + a_{44}\dot{\theta}_v + \frac{C_F}{m}\delta \right] d_{ZtoRA} + r_v \cdot u$$

$$= \left[a_{11} + a_{21}d_{xtoYA} + a_{41}d_{ztoRA} \right] \dot{y}_v \tag{7}$$

$$+ \left[a_{12} + a_{22}d_{xtoYA} + a_{42}d_{ztoRA} + u \right] r_v$$

$$+ \left[a_{43}d_{ztoRA} \right] \theta_v$$

$$+ \left[a_{44}d_{ztoRA} \right] \dot{\theta}_v$$

$$+ \left[\frac{C_F}{m} + \frac{C_F a}{I_z}d_{xtoYA} + \frac{C_F}{m}d_{ztoRA} \right] \delta$$

where a_{kl} is the element in the k row and l column of the matrix A, d_{xtoYA} is the distance along the x axis from a sensor to the yaw axis, and d_{ztoRA} is the distance along the z axis from the sensor to the roll axis.

[0021] The model for vertically oriented sensors is

$$A_{z,meas} = -g + \ddot{\theta}_v d_{yraRA} \qquad (8)$$

Hence, from Equations (2) and (5)

$$a_{z,body} = -g + \left[a_{41}\dot{y}_v + a_{42}r_v + a_{43}\theta_v + a_{44}\dot{\theta}_v + \frac{C_F}{m}\delta \right] d_{ytoRA}$$

$$= \left[a_{41}d_{ytoRA} \right] \dot{y}_v$$

$$+ \left[a_{42}d_{ytoRA} \right] r_v$$

$$+ \left[a_{43}d_{ytoRA} \right] \theta_v \qquad (9)$$

$$+ \left[a_{44}d_{ytoRA} \right] \dot{\theta}_v$$

$$+ \left[\frac{C_F}{m}d_{ytoRA} \right] \delta$$

$$+ \left[-g \right] \qquad ,$$

where d_{ytoRA} is the distance along the y axis to the roll axis.

[0022] And for longitudinally oriented sensors, the sensor model is provided by the expression

$$A_{x,meas} = -\dot{r}_v d_{ytoYA} \qquad (10)$$

such that upon employing Equations (2) and (5), Equation (10) becomes

$$a_{x,body} = -a_{21}d_{dytoYA}\dot{y} \qquad (11)$$

$$- a_{22}d_{dytoYA} r_v$$

$$-b_{21}d_{ytoYA}\delta$$

where d_{ytoYA} is the distance along the y axis to the yaw axis and b_{21} is the element in the second row and first column of the matrix B.

[0023]   The algorithm implemented in the estimator 26 processes the expressions from Equations (7), (9), and (11) through a filter (an estimation algorithm) to provide the estimates for the state vector $\bar{x}_v = \begin{bmatrix} \dot{y}_v & r_v & \theta_v & \dot{\theta}_v \end{bmatrix}^T$.

[0024]   Note that the above discussion is directed to obtaining a solution for the state vector $\bar{x}_v$ in continuous time.   Therefore, $\dot{\bar{x}}_v$, is typically discretized according to the expression

$$\bar{x}_v(k+1) = A_d\bar{x}_v(k) + B_d\bar{u}(k) \tag{12}$$

where k identifies the kth time step and the matrices A and B can be discretized according to the approximations

$$A_d = I_n + \Delta_k \cdot A$$

and $B_d = \Delta_k \cdot B$

where I_n is the nth order identity matrix, which in this case is a fourth order identity matrix, and Δ_k is the time step.

[0025]   Although the above embodiment is directed to a sensor set with linear accelerometers, hybrid-sensor-sets are contemplated. For example, an angular rate sensor can be used in the vehicle 12 and a model of that sensor can be used in the "Kalman Filter" box 20. Specifically, for a yaw rate sensor, the model is [0 1 0 0], that is, the sensor measures yaw rate and nothing else.

[0026]   Hence, in stability control, in which measuring yaw rate and roll rate/angle is useful, four accelerometers can be used for the sensors 14. Alternatively, for a hybrid system, two accelerometers and an angular rate sensor may be employed. Other examples of hybrid systems include, but are not limited to, two lateral and two vertical accelerometers; two lateral, two longitudinal, and two vertical accelerometers; and two lateral, two vertical accelerometers, and an angular rate sensor.

[0027]   Other embodiments are within the scope of the claims.